Towards a Sustainable Nuclear Energy System

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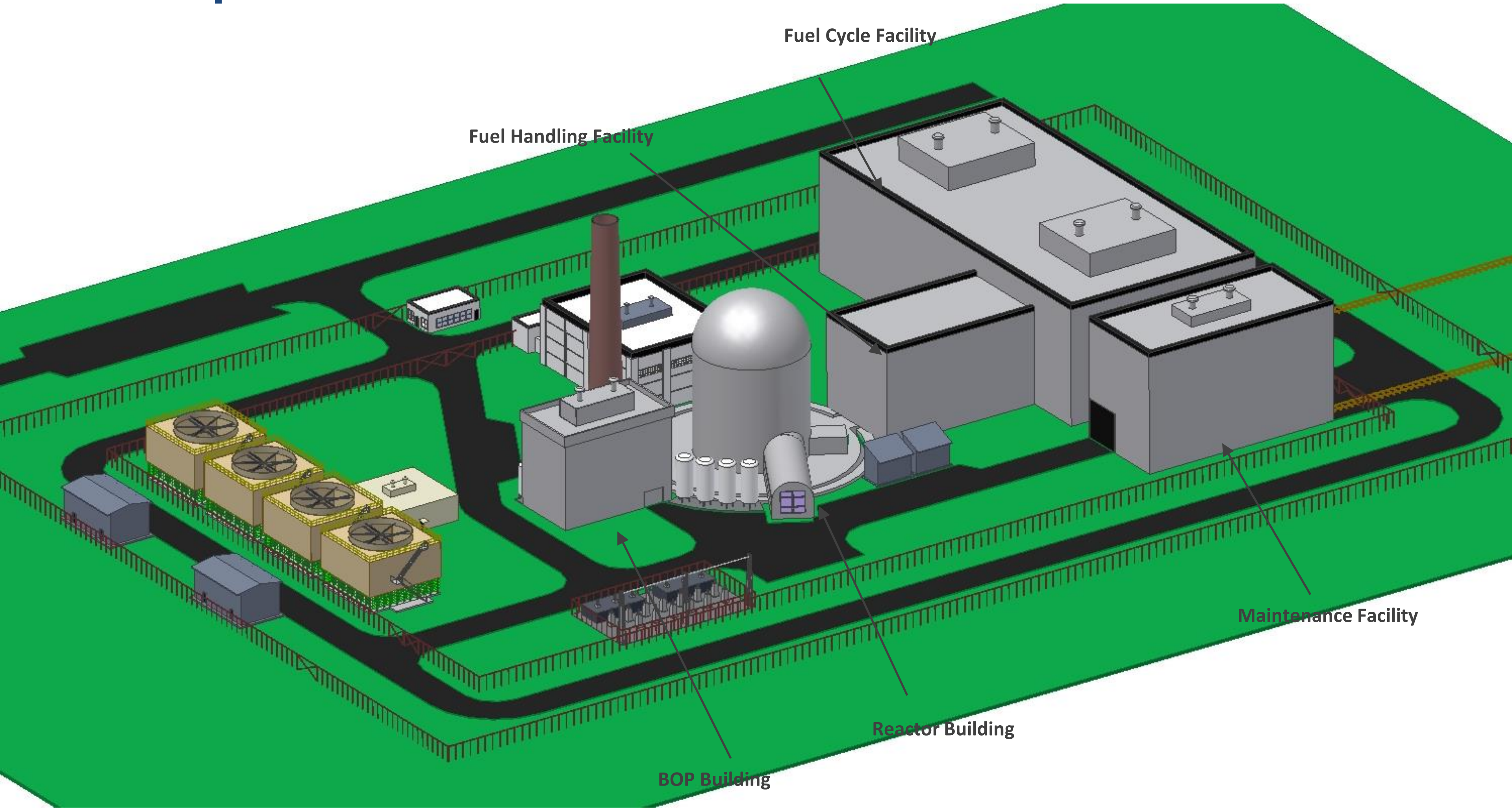
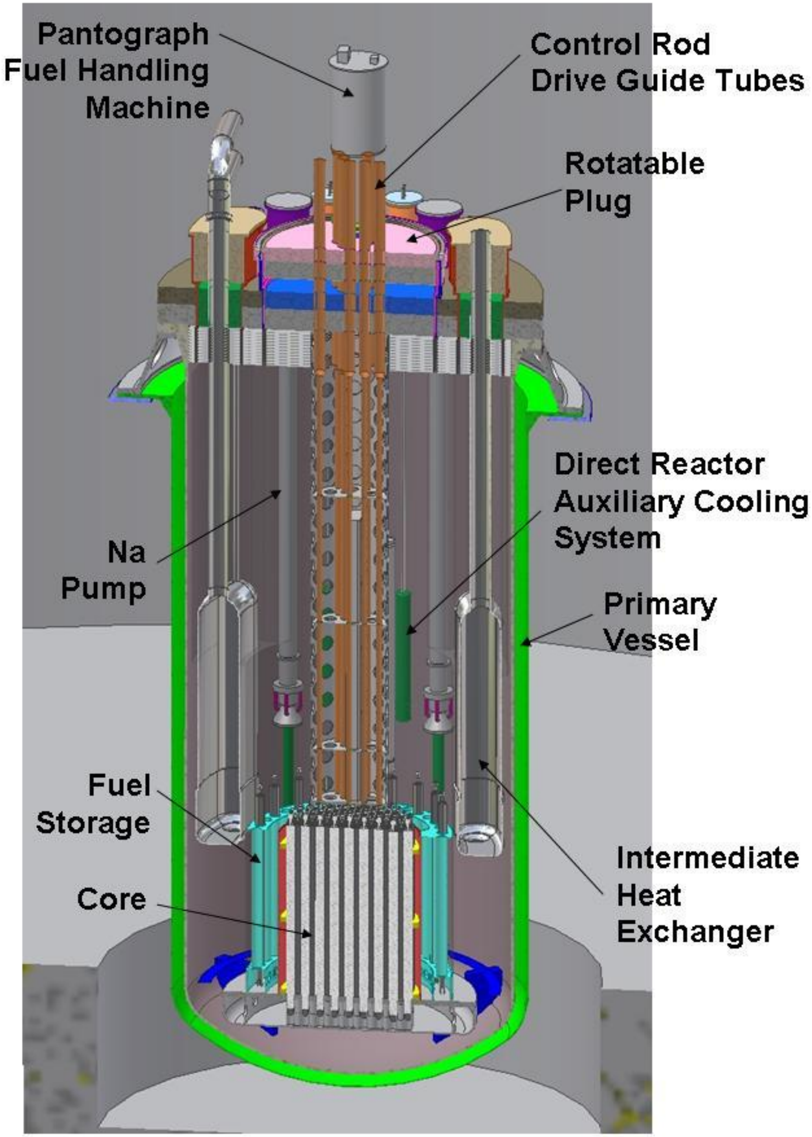
Conceptual Advanced Fast Reactor Site Plan



- Close-coupling of reactor and fuel recycle facility at the reactor park allows for efficient fuel multi-recycle
  - Results in off-site transport of engineered waste forms not used fuel

Advanced Fast Reactor Systems



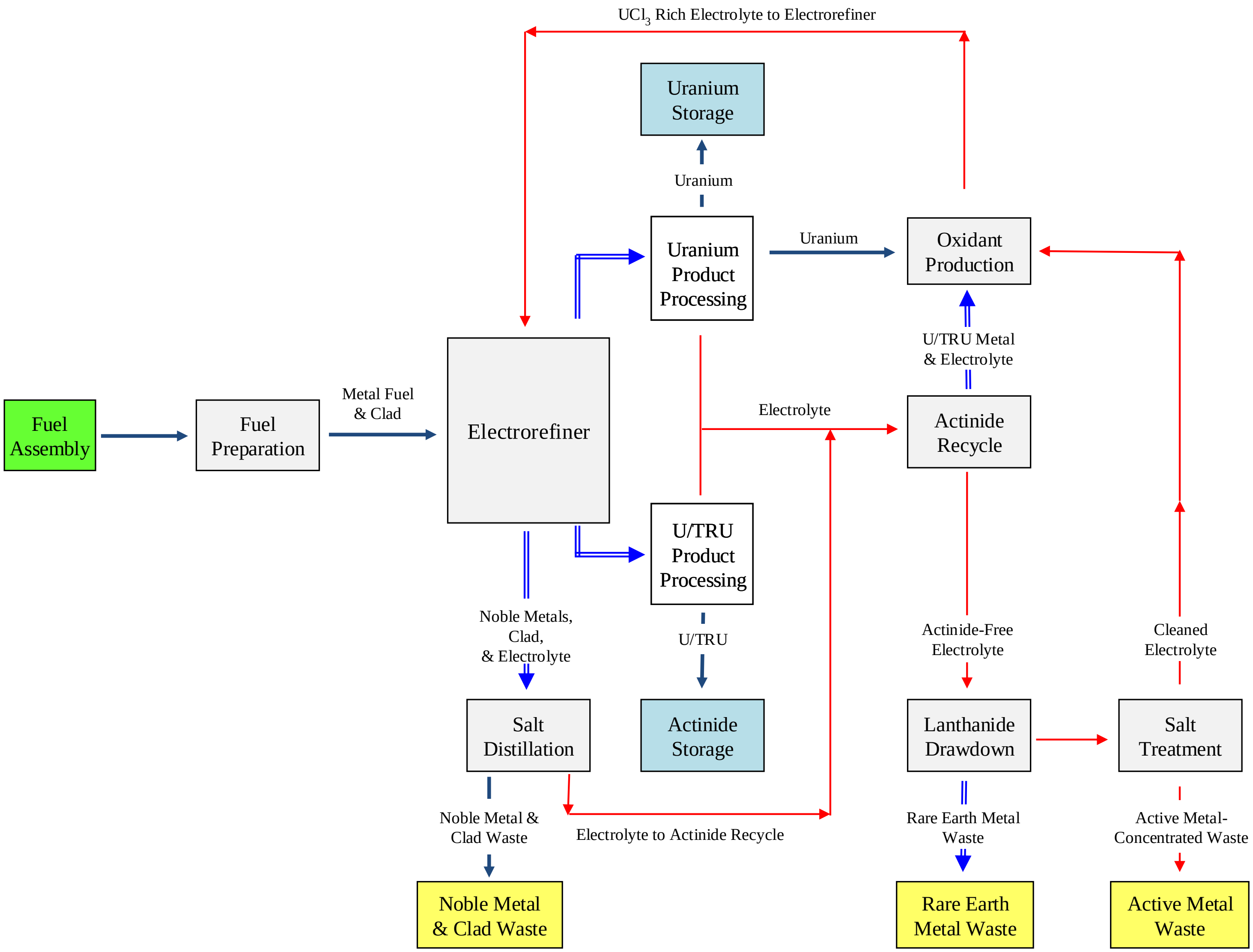
- Advanced fast reactor systems have unique features that impact choice of reprocessing technology
  - Metal fuel
  - High concentration of transuranic elements in fuel (e.g., 20 wt%)
  - Short cooling time to allow for in-vessel storage of used fuel prior to reprocessing
    - No extensive out-of-reactor used fuel storage system required
    - Eliminates large out-of-reactor inventory of transuranic elements
  - Sodium used for bonding metal fuel meat with cladding material for improved heat transfer
    - Reacts to form sodium chloride that is soluble in molten salt

Technology Development Objectives

Develop next-generation fuel cycle and waste management technologies that enable a sustainable fuel cycle

- Industrially practicable and economical
  - High capacity factor, remote operation requiring limited intervention, modular systems to facilitate repair, low maintenance
  - Minimal impact on overall cost of electricity
- Safeguardable system that meets U.S. non-proliferation objectives
  - Move away from using terminology proliferation-resistant
  - Focus on quantifiable rather than qualitative characteristics of the system
- Maximize actinide recovery to maximize resource utilization and provide potential enhancements to future high-level waste repository
- Encapsulate fission products in engineered waste forms that can be disposed in an environmentally responsible manner

Conceptual Flowsheet for Treating Used Metallic Fuel



Electrorefining Technology

- Electrorefining is primary unit operation in used fuel treatment process
  - Anodic dissolution of used fuel
  - Cathodic deposition of actinides for recycle

- Uranium electrorefining is most mature of all pyrochemical technologies
  - Process viability demonstrated through laboratory- and engineering-scale testing with simulated and irradiated fuel
  - Sustained treatment of irradiated fuel in a remote environment demonstrated during treatment of fuel from Experimental Breeder Reactor II (Mk IV and V electrorefiners)

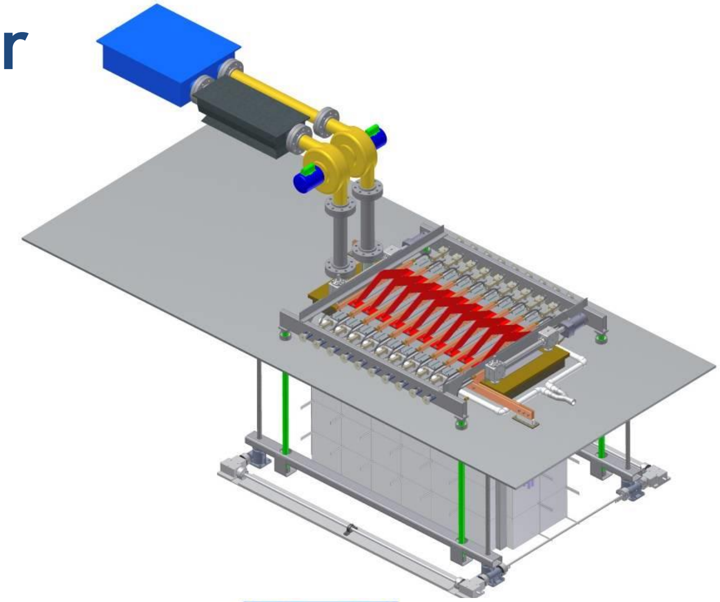
- Advanced design developed to eliminate process inefficiencies identified during EBR II fuel treatment (Mk IV and V refiners)
  - Scalability
  - Product Recovery
  - Process efficiency

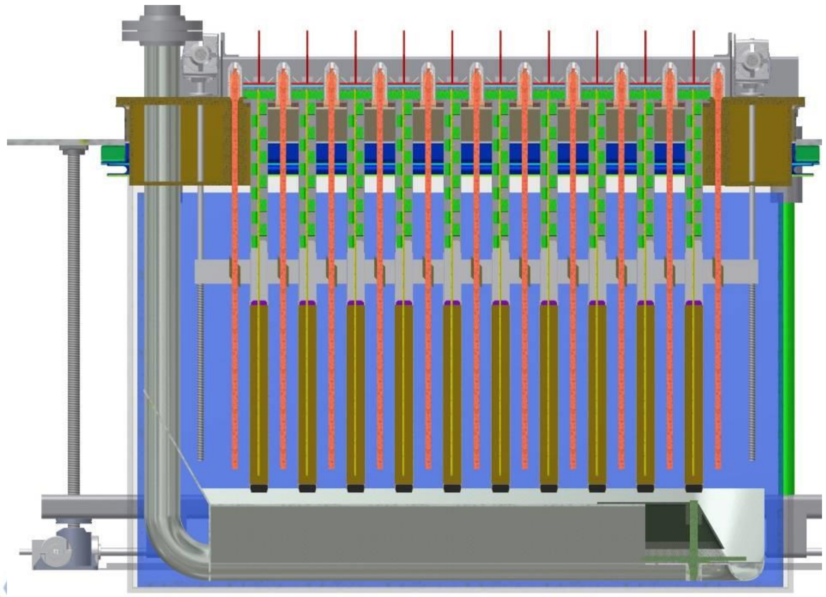
Planar electrorefiner prototype module

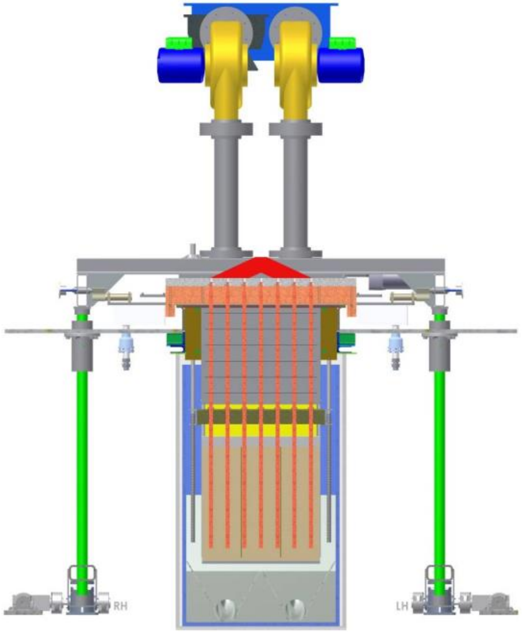
Dendritic U product

Next-Generation Electrorefiner

- Industrialization of technology addressed through process efficiency and scalability improvements
  - Modular approach improves scalability and throughput
  - Intermittent product removal from cathodes enhances process efficiency
  - Automated product recovery enhances throughput
  - Design allows simultaneous recovery of U and co-deposited U/TRU products







General Electric - Hitachi Nuclear
Patent Application: US20130161186

Approaches to U/TRU Recovery

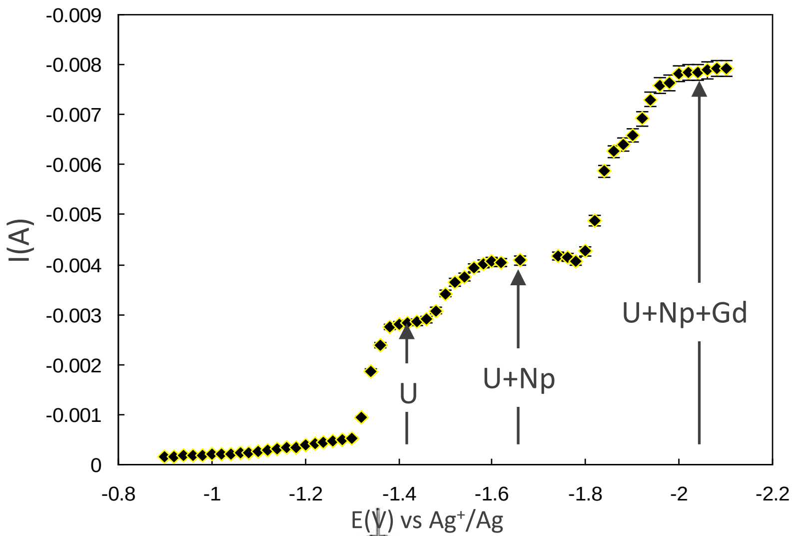
- Alloy-forming liquid metal cathode (e.g., cadmium)
  - Deposition potential for TRU (and lanthanides) is shifted to less cathodic values
    - Decreases separation between TRU and lanthanide metals
  - Requires subsequent TRU separation from alloy and residual salt
  - Process demonstrated at kilogram-scale with irradiated materials
    - Issues with control of dendrite formation on surface of recovery crucible
    - Materials compatibility issues

- Non-alloying solid metal cathode
  - High current density at cathode shifts cathode potential to more cathodic values as cathode current density exceeds U^{3+} mass transfer limiting current
  - Maximum separation between TRUs and lanthanides, limits lanthanide contamination of product and mitigates fuel clad chemical interactions
  - No alloy forms with the cathode material
  - Low melting U-TRU alloy makes metal - residual salt separation via bottom-pour feasible

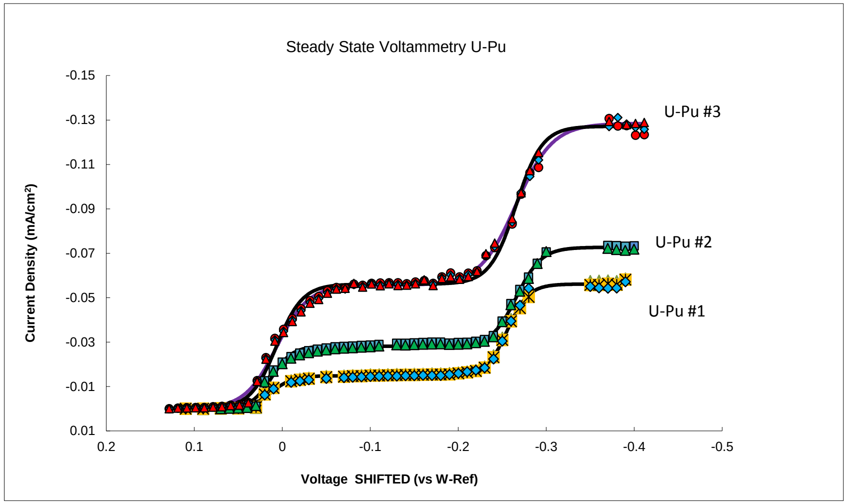
- R&D efforts focused on developing solid cathode technology for U/TRU recovery

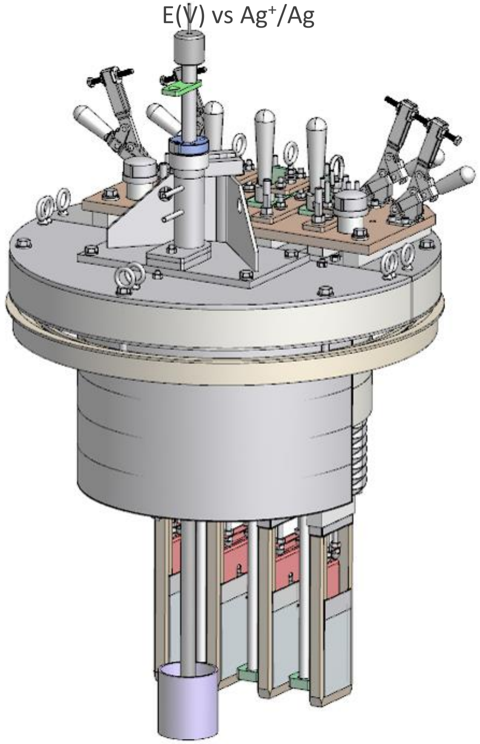
U/TRU Co-deposition Studies

- U/TRU co-deposition studies focused on evaluation of process at the kilogram scale using uranium and TRU surrogates (lanthanides)
  - Laboratory –scale tests revealed
    - Clear plateaus at potentials consistent with thermodynamic predictions
    - Current levels proportional to relative concentrations of U, Np, and Gd
  - Understand boundary conditions for U/TRU recovery from laboratory-scale tests



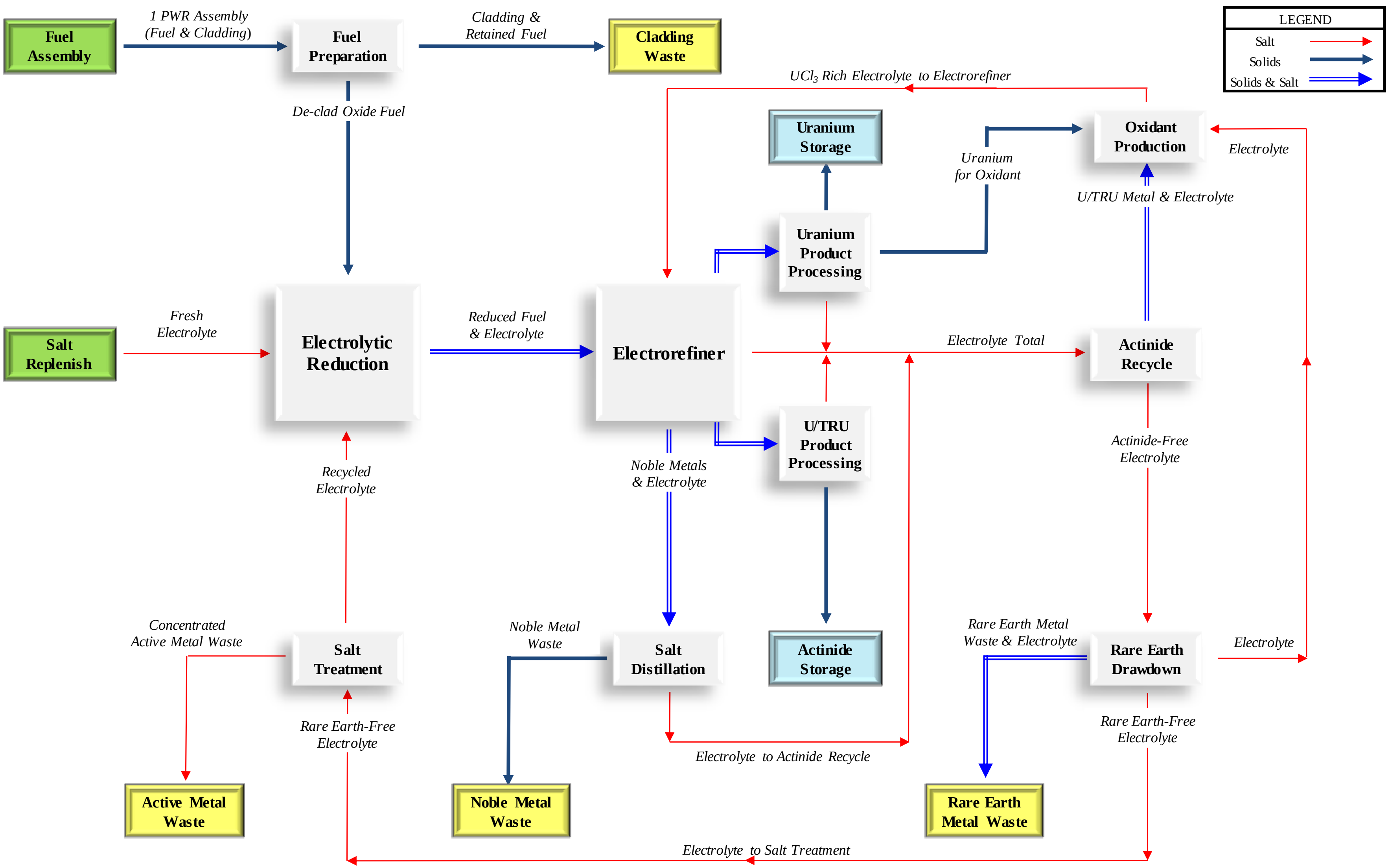
- Test apparatus being used to evaluate simultaneous U deposition and U/TRU co-deposition and co-deposition system performance





Sketch of co-deposition test system

Conceptual Flowsheet for Treating Used Oxide Fuel



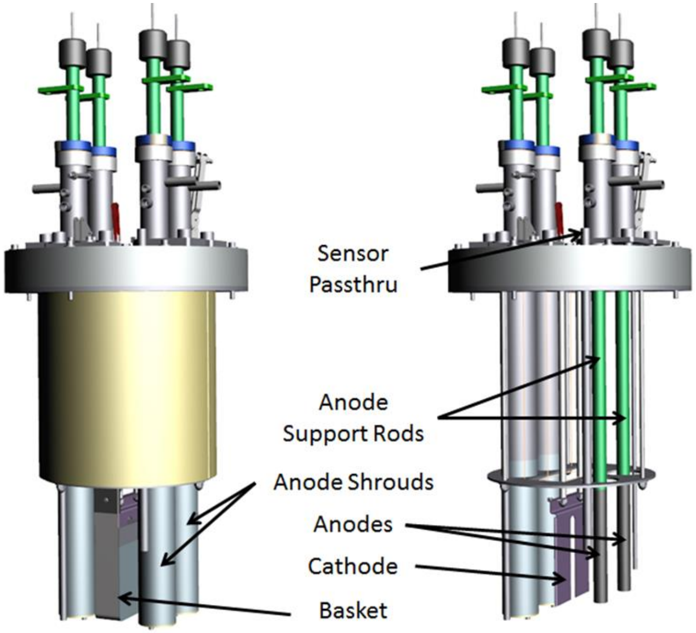
Electroreduction Technology

- Electroreduction converts used fuel oxides to base metals for treatment in electrorefiner
  - Anode process produces oxygen gas that is swept from cell
  - Cathode process yields metallic product suitable for electrorefining
  - LiCl - Li_2O solvent @650°C

- Process chemistry demonstrated through tests with simulated (ANL) and irradiated LWR and fast reactor MOX fuel (INL**)**

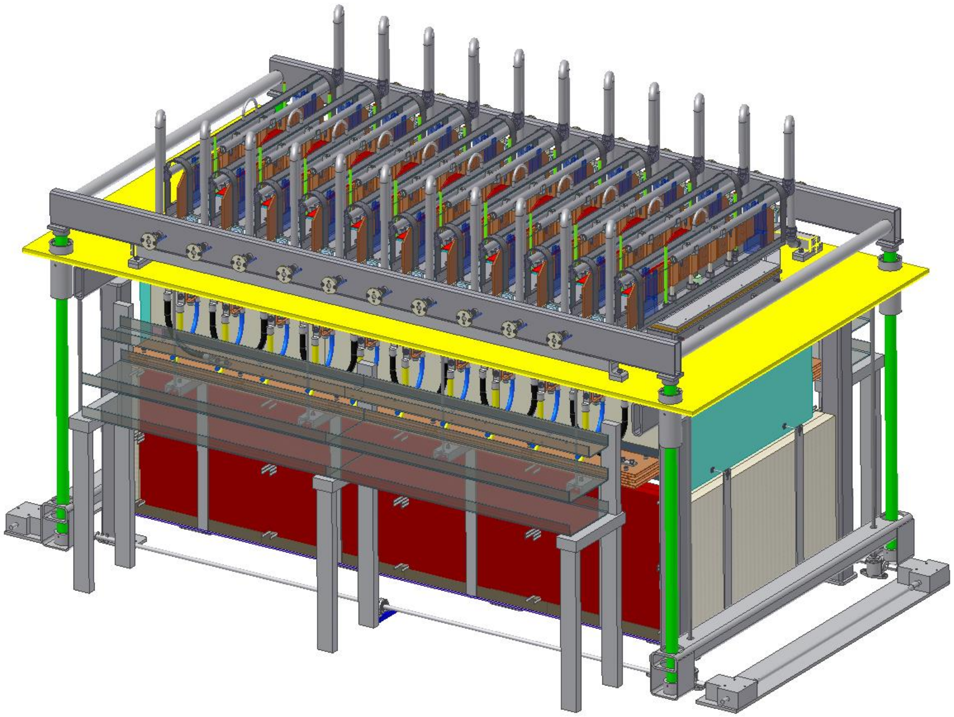
- High-capacity cell studies
  - Kilogram-scale demonstrations of process yielded high current efficiency and efficient oxygen gas removal from cell
  - Reduction rates are very good; cells designed to collect fundamental data
  - Fission products have no effect on conversion process

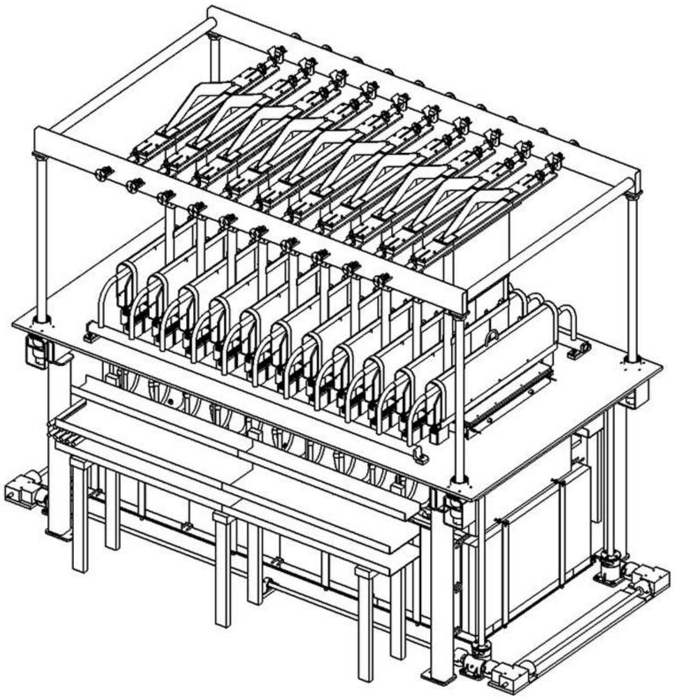
- Process development activities now focused on anode materials testing and process monitoring



Kg-scale anode test rig

Next-Generation Electroreducer





- Design developed based on Pt-anode technology but design flexibility allows incorporation of alternative anode materials

General Electric - Hitachi Nuclear
Patent Application: US20120160666

Process Development Challenges and Opportunities

- Significant effort focused on back-end of flowsheet
  - Maximize actinide recovery
    - Crucial to reducing long-term radiotoxicity and heat load of high-level waste going to a geologic repository
    - Recovered actinides recycled to the treatment system
  - Recover *right amount* of fission products from process salt to achieve actinide product quality and minimize waste destined for repository
    - No need to produce high purity salt for recycle
    - Constitution of recovered fission products enables encapsulation in durable waste forms
  - Salt treatment processes should not add complexity or significant cost to the fuel treatment facility

- Process options identified, reviewed, and preferred options down-selected for development
  - Electrolysis
    - Actinide drawdown
    - Lanthanide drawdown
  - Two options being explored for alkali and alkaline earth elements
    - Fractional crystallization with LiCl-based salt system
    - Electrochemical ion-selective membrane with eutectic salt system (Sandia National Laboratory)

Actinide and Lanthanide Drawdown via Electrolysis

- Electrolysis can be used for recovery of actinide metals from molten salt solutions
  - Routinely used in industrial-scale production of specialty metals
  - High degree of separation of actinides from the salt
  - Recovered actinides recycled to the treatment system
  - Recovered lanthanides incorporated into a durable waste form
  - Actinide and lanthanide drawdown can be performed sequentially in the same process equipment
  - Significantly decreases the amount of the high-level waste generated in the electrochemical treatment process without adding additional complexity

- Actinide recovery (e.g., U, Pu) demonstrated during initial feasibility experiments with earlier system

Electrolysis demonstration system

Operation Modeling of Drawdown Process

- In electrolysis, there is a continuous change in the composition of the salt
  - Actinide deposition potential becomes more negative as their concentration in salt decreases
  - Operating potential has to be adjusted to more negative values as process proceeds
  - Depending on the extent of separation, the values can be negative enough to deposit lanthanides along with the actinides

- Theoretical treatment of electrolysis process revealed the better the recovery of actinides, the poorer the separation between actinides and lanthanides
  - For 99.9% Am recovery, majority of lanthanides will co-deposit
  - For 65% Am recovery, almost complete separation can be achieved
  - All calculations are based on assumption of Am^{2+} in salt phase

- **Better understanding of Am chemistry (Am^{2+}/Am^{3+}) required under process relevant conditions**

- Currently determining formal electrochemical potentials for U, Np, Pu and Am under a consistent set of concentration and salt conditions
  - Results will guide selection of operating conditions for electrolysis system

Summary

Electrochemical process development is moving us towards a sustainable nuclear energy system

- Next-generation refining and reduction systems ready for evaluation
  - Electroreduction provides bridge between light water reactors and fast reactors for fuel cycle closure
  - U/TRU co-deposition system can be incorporated into electrorefiner as it becomes available

- Development and testing of salt treatment systems is occurring at laboratory- and/or engineering-scale
  - No showstoppers identified; scale-up and throughput requirements can be met for multiple fuel treatment scenarios
  - Additional thermodynamic data needed for minor actinides under process relevant conditions is being collected and will guide engineering-scale system development
  - Experimental work augmented by focused modeling activities

- Process monitoring and control technologies are integral to electrochemical process development
  - May be useful indicators for material diversion and material control and accountancy measurements

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